SoLid Reactor Neutrino Detector
- AAP 2018 -

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on behalf of the SoLid collaboration

Applied Antineutrino Physics Conference 2018, Livermore

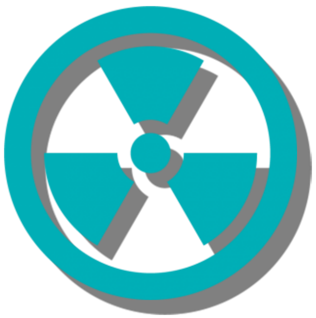
October 10, 2018

Overview

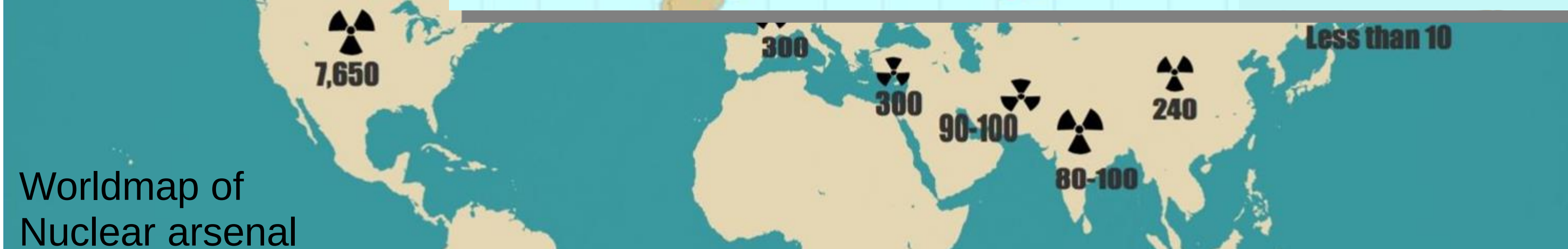
- **The nuclear era**
- The SoLid neutrino detector @ the BR2 reactor
- Detector specifications
- Detector construction and operation
- Data taking

Nuclear era

- Worldwide nuclear reactor facilities and nuclear weapon arsenal
- Require close monitoring and safeguard
- Nonproliferation goals of transparency, cooperation and peaceful use



Worldmap of nuclear reactors



Worldmap of Nuclear arsenal

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Monitoring and safeguard - Objectives

- (Remotely) detect change in operational status of reactor
- Observe change of fuel composition after refueling
- Make precision measurement of fuel spectra

→ neutrinos can do the job

Uncontainable, unaffected by test conditions, specific to fission

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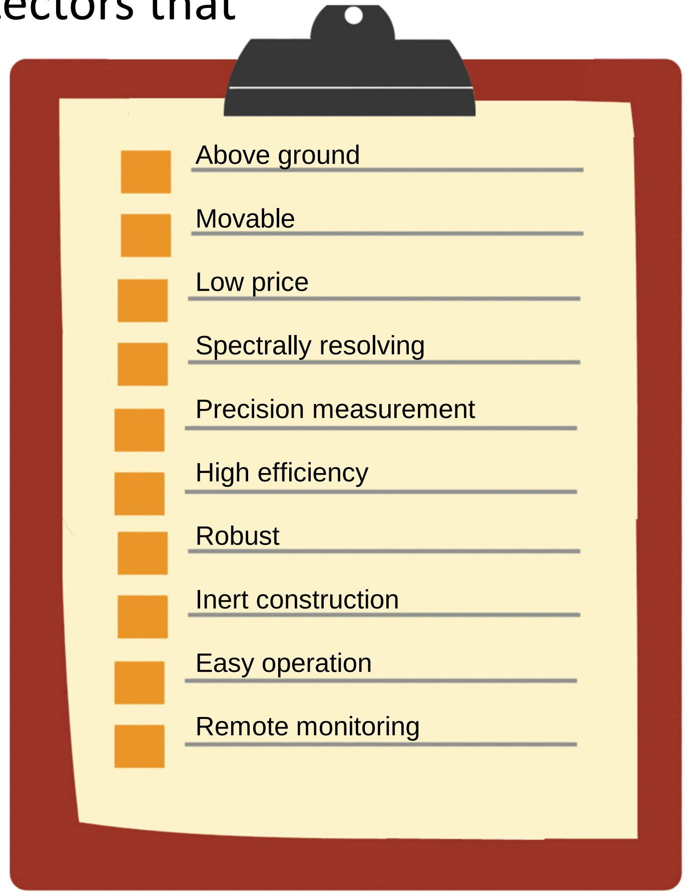
Monitoring and safeguard - Requirements

- Suitable neutrino detectors that meet our demands



- When possible, access to nuclear facility
- Engagement with reactor monitoring authorities and operators

Overview

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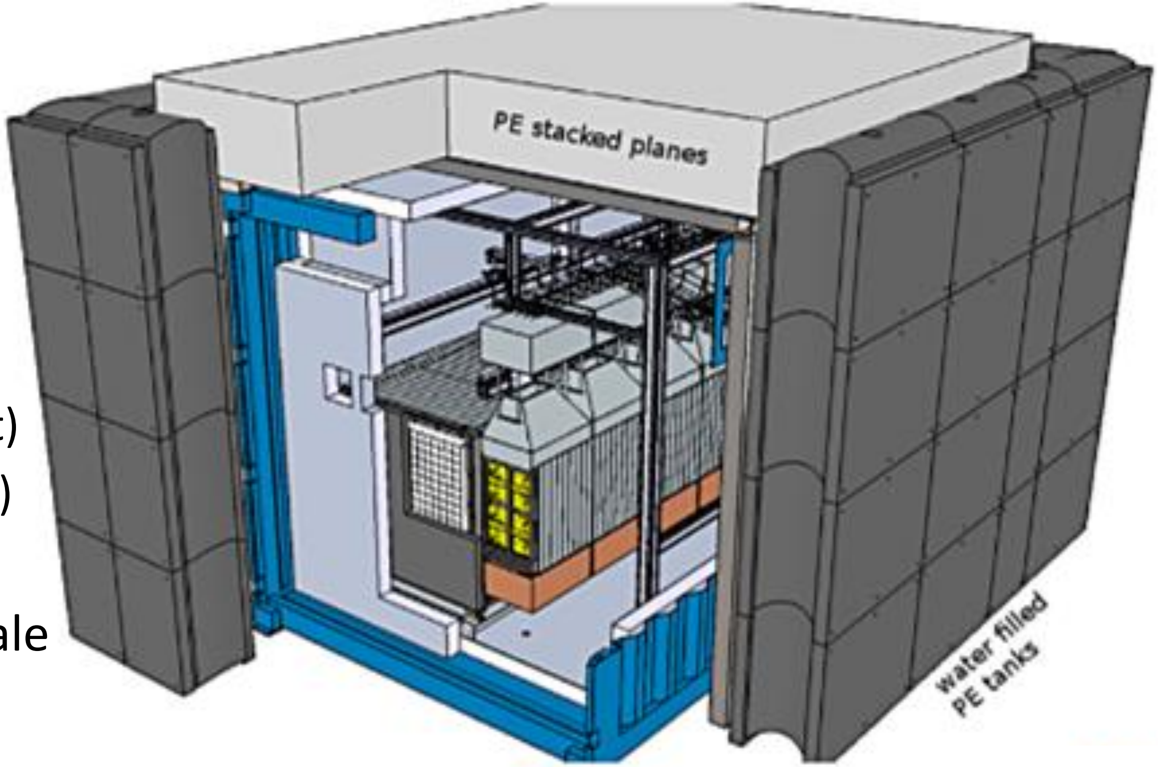
SoLid Phase 1 detector

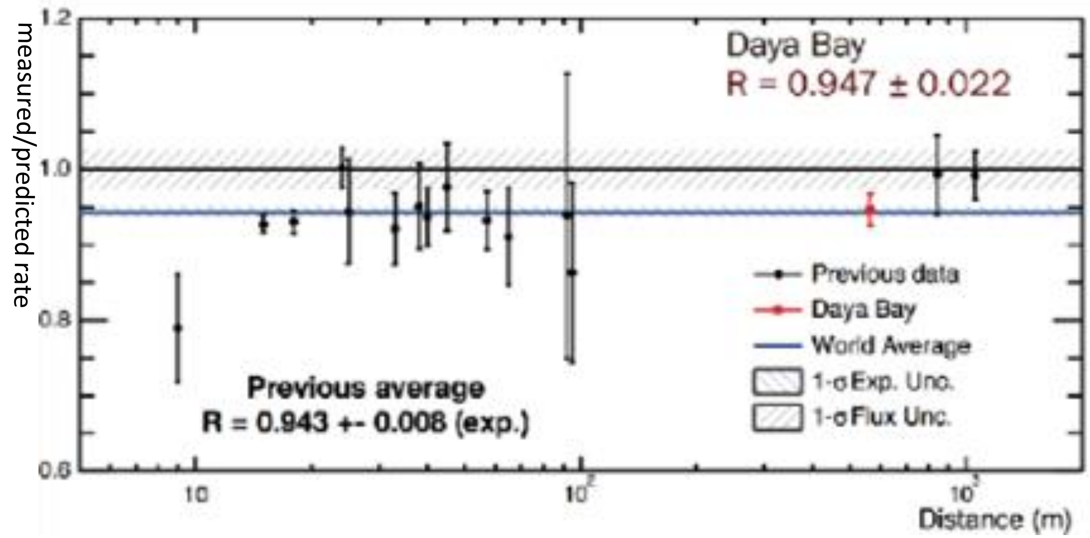
- In movable shipping container (2,4 x 2,6 x 3,8 m^3)
- Non flammable, solid scintillator technology
- High segmentation gives good position and energy resolution
- Above ground operation
- Easy, remote monitoring
- Shielded by
    - Cadmium sheets
    - Water walls (50cm x 3,4m, 28t)
    - Polyethylene ceiling (50cm, 6t)
- Automated calibration system for absolute efficiency and energy scale calibration at % level

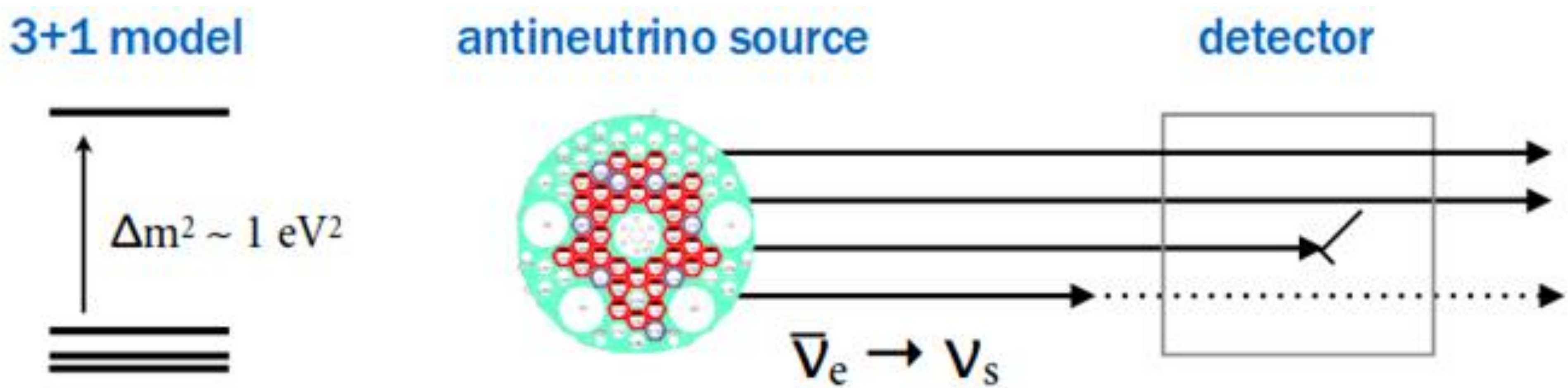


→ Full Geant4 simulation

Science motivation

- Unexpected active neutrino oscillations were measured
- Explanation by additional mass state, as correction to 3x3 neutrino mixing
- Sterile neutrino only measurable indirectly through active states



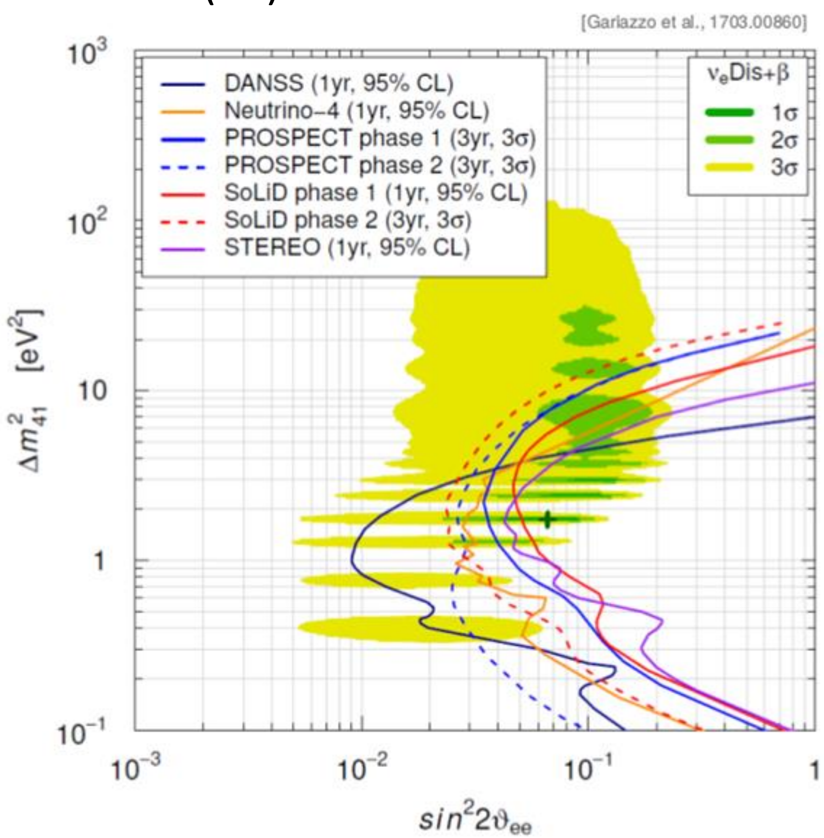


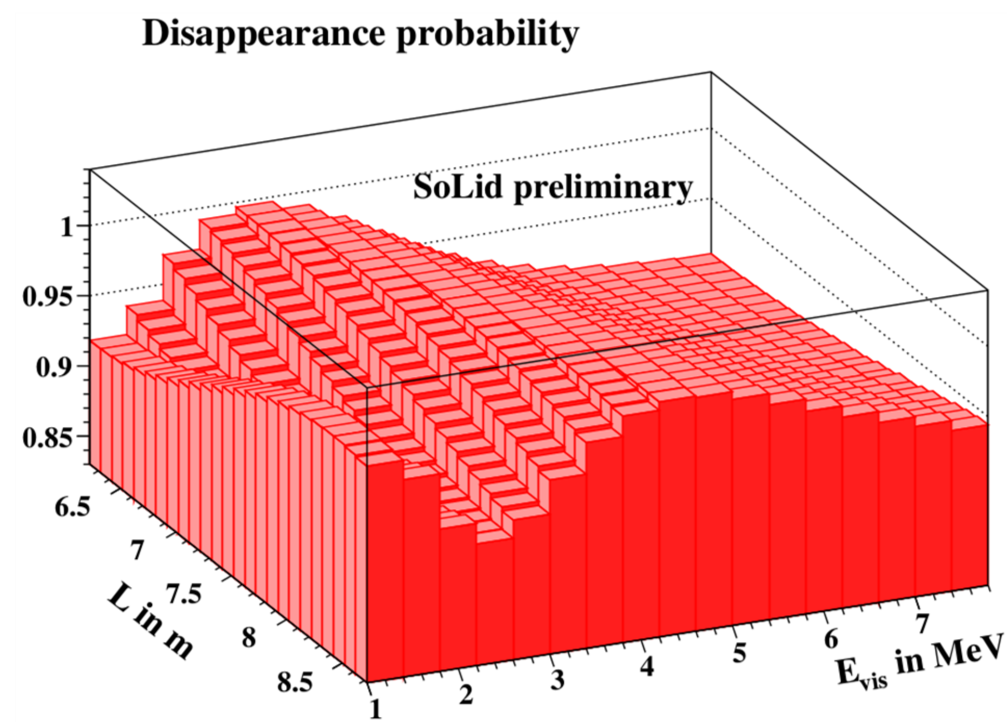
SoLid Sensitivity to Sterile State

$$P_{ee} \sim 1 - \sin^2(2\theta_{14})\sin\,(1.267\Delta m_{14}^2\, L[m]/E[MeV]\;)$$

- Oscillation dictated by properties of sterile neutrino
- Best fit gives Δm² ~ 1.73 eV² and sin²(2θ) ~ 0.1

- Oscillation apparent over distance and energy
- Coverage in L/E requires a good position - and energy resolution

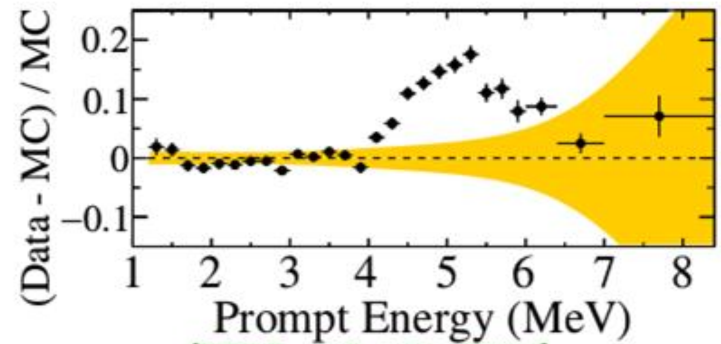




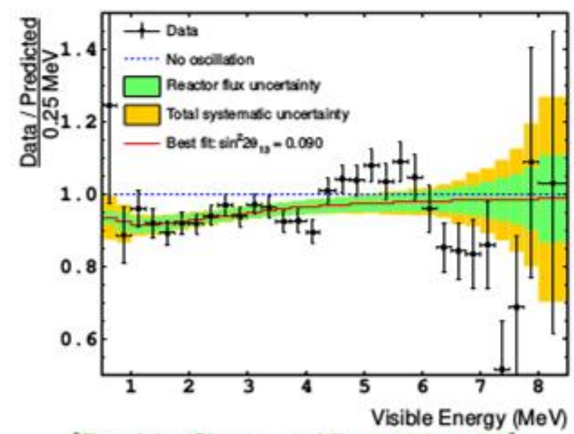
Reactor spectrum distortions

- Energy spectrum distortions observed by long baseline reactor experiments using common fuels (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu)

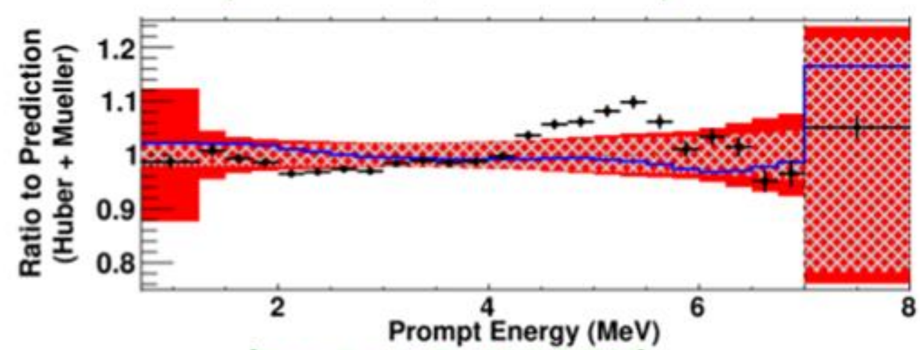
- Demands new measurement close by compact reactor core with simple fuel composition
- Reactor site poses safety -and security implications



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



[Daya Bay, arXiv:1508.04233]

BR2 nuclear site

- Pure fuel of 93.5% ^{235}U
- Compact research reactor
- ⌀ 50 cm and heigth 90 cm
- Thermal power 50-80 MW
- Duty cycle 150 days/year (~1month cycles)
- SoLid at baseline 6-9 m
- Experimental access ports on axis with reactor core

- At ground level
  - Overburden 10 m.w.e.
  - Muon rate O(250Hz)
  - Cosmogenic neutrons
  - Natural radioactivity

SoLid and the SCK-CEN

- SCK-CEN has long history of positive proliferation
  - Production of medical isotopes
  - Research of radioactive waste disposal
  - Construction of multipurpose reactor for high tech application (MYRRHA)
- Close cooperation
  - Acces to high security area in confinement building, close to BR2 reactor core (under Euratom safeguard)
  - SoLid researchers employed by SCK-CEN

SoLid

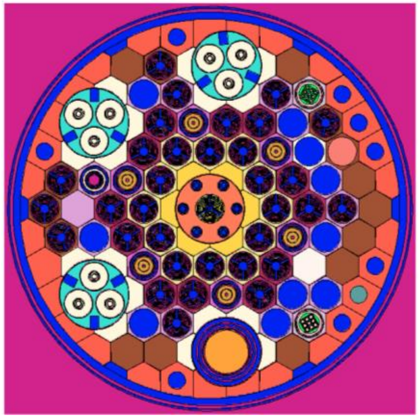
Reactor simulation antineutrino spectrum

- Share experiences
  - BR2: very complex geometry, take advantage of simulation work performed by SCK-CEN and comparison with reactor measurements
  - Strong expertise on reactor/antineutrino spectrum calculations @SUBATECH since Double Chooz

S. Kalcheva et al, Mathematics & Computational Methods Applied to Nuclear Science & Engineering Conference, Korea, 2017

L. Giot et al., European Research Reactor conference, Bucharest, 2015

M. Fallot et al., PRL 109, 202504 (2012) & Z. Issoufou et al., PRL 115, 102503 (2015)

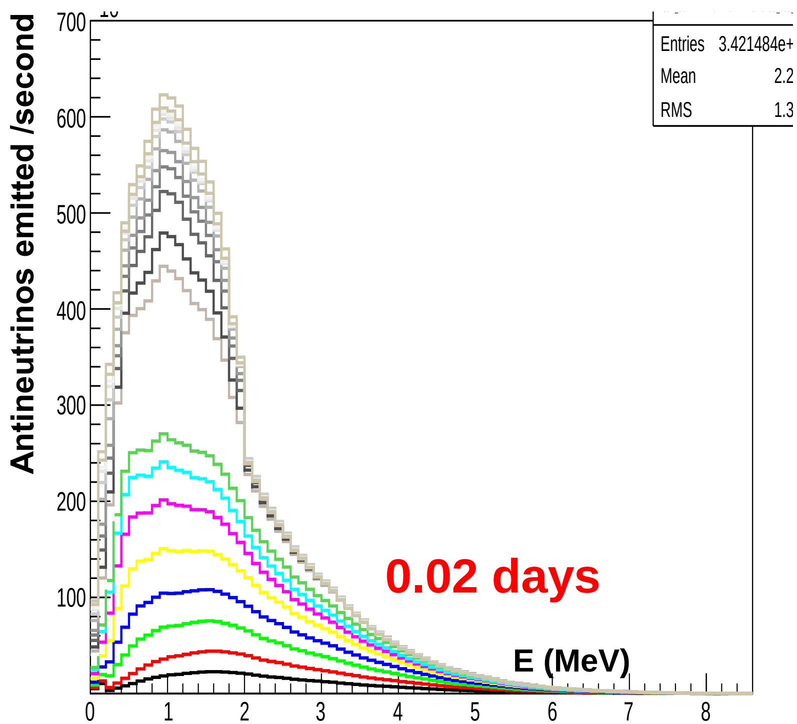


BR2 MCNPX simulation

twisted hyperboloid fuel bundle

^{235}U enrichment 93 wt%

- Conversion and Summation Method are foreseen
- Antineutrino spectrum for cycle 01-2015 (SM1 data taking), ex: summation method =>
- Calculation of systematic errors associated with the emitted antineutrino spectrum and production phase for the 2018 cycles



SoLid

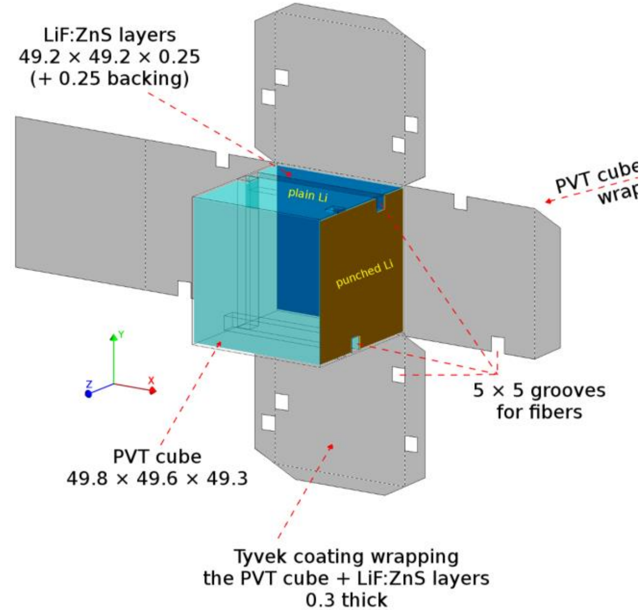
Overview

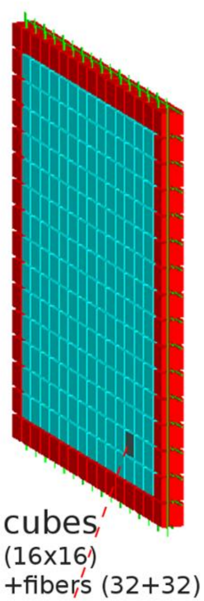
- The nuclear era
- The SoLid neutrino detector @ the BR2 reactor
- **Detector specifications**
- Detector construction and operation
- Data taking

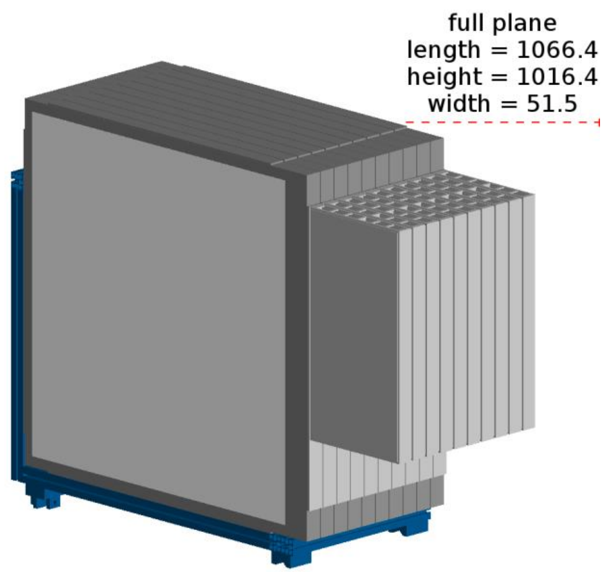
SoLid Phase 1 detector

JINST 12 (2017) no.04, P04024
JINST 13 (2018) no.05, P05005

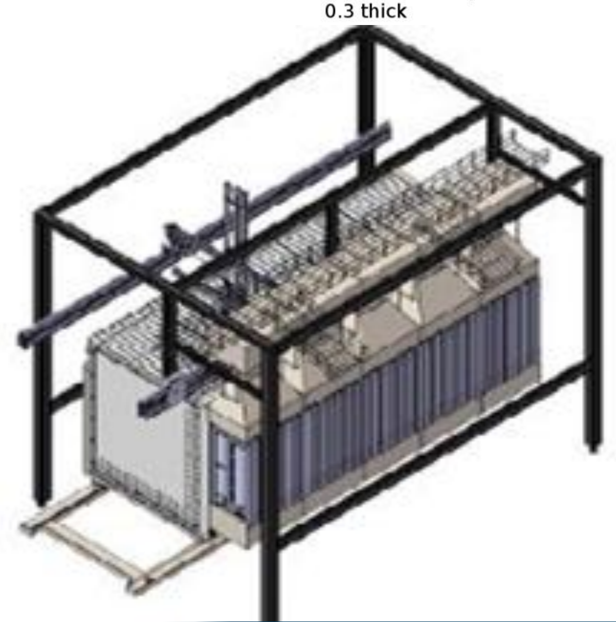
- 5cm cubes give resolution on 3D topological information
- 16x16 cubes stacked in planes
- Planes grouped per 10 in 5 modules,
- Modules installed on movable rail system
- 1.6t fiducial mass







Phase1 module = 10 full planes



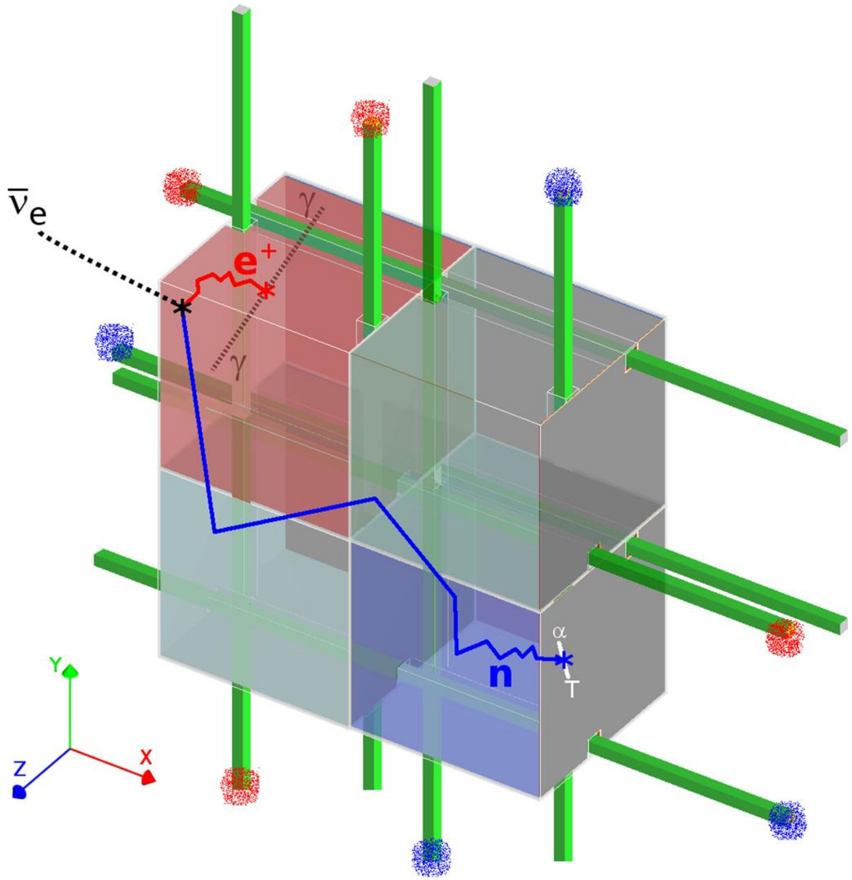
SoLid detection principle

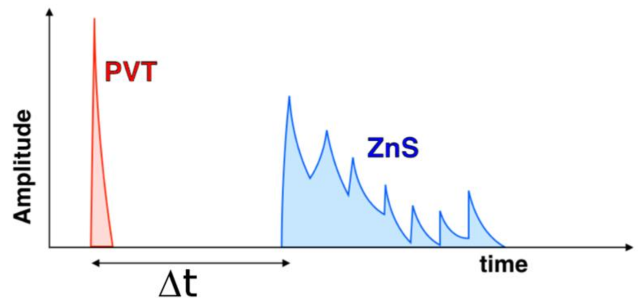
- Reactor neutrinos detected through inverse beta decay (IBD) in the composite scintillator elements

  $\overline{\nu}_e + p \rightarrow e^+ + n \qquad (E_{\overline{\nu}_e} > 1.8 \text{ MeV})$

- Prompt positron signal
  - Positron energy contained in PVT cube
  - Allows localisation of interaction
  - Gives the anti-neutrino's energy

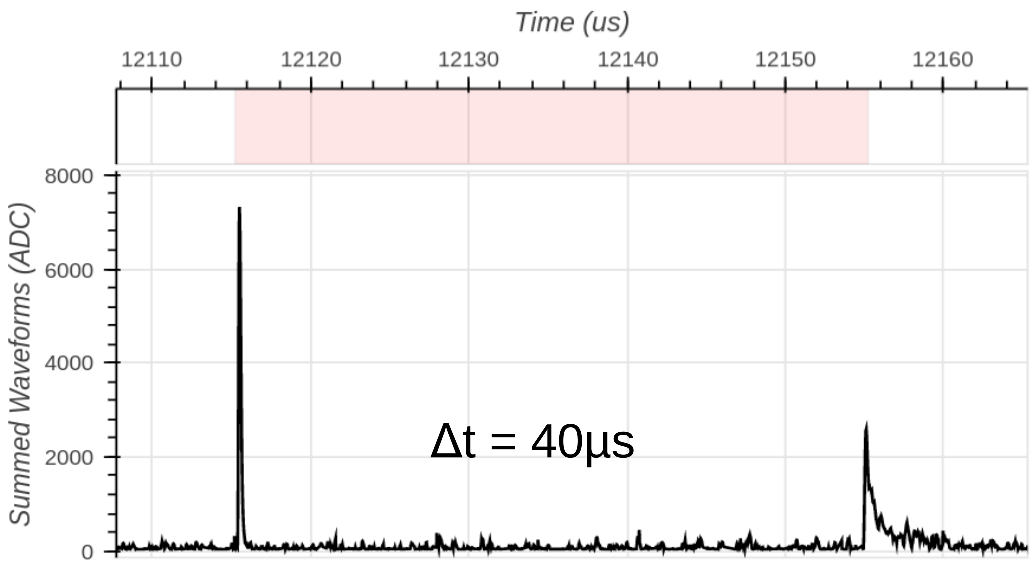
- Delayed neutron signal
  - Neutron captured in 6LiF:ZnS close to interaction
  - $n + {}^6Li \rightarrow {}^3H + \alpha \qquad + 4.78 \text{ MeV}$

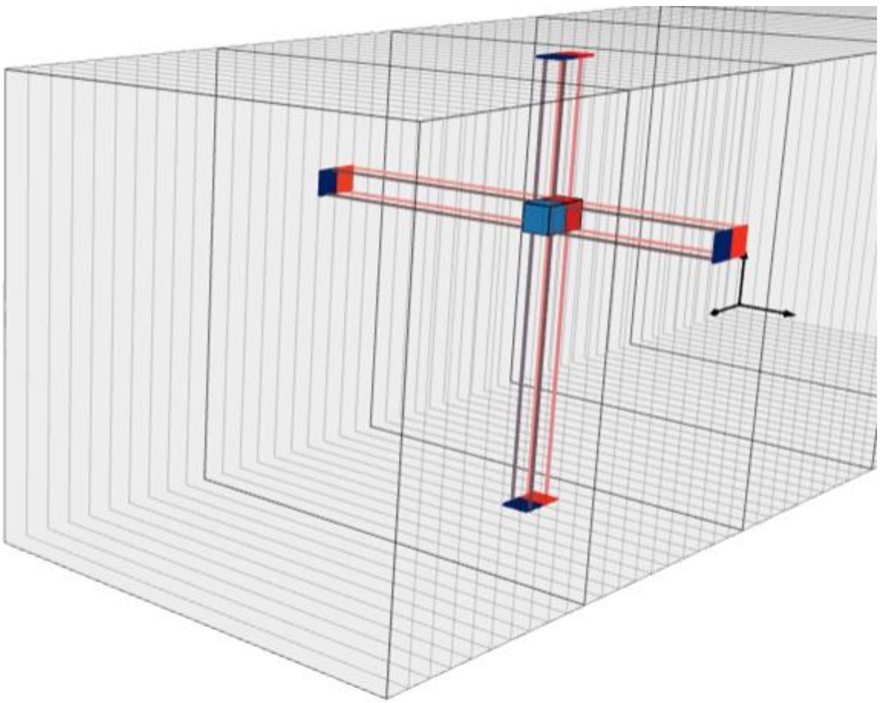




SoLid signal

- Example of prompt and delayed coincidence from first reactor cycle in december 2017



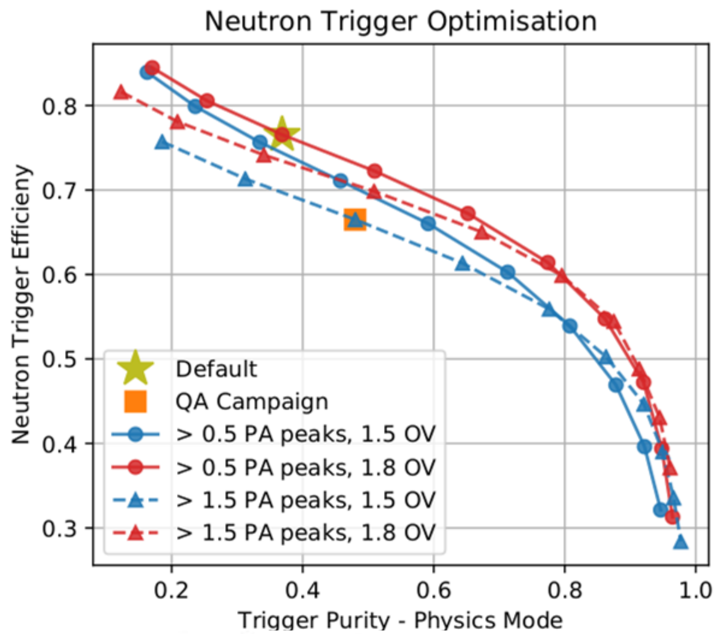


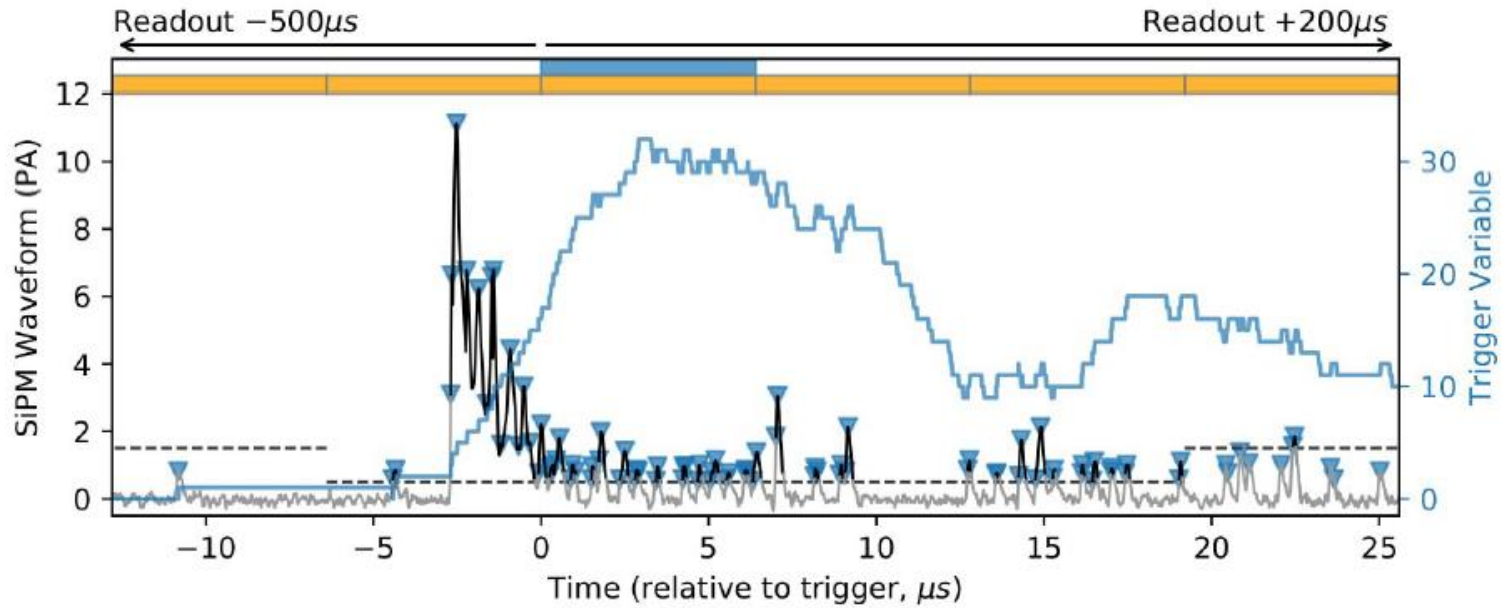
- Rates of detection signal and background

Signal	Detector Interaction Rate
Dark Count (SiPM)	100 GHz
Reactor γ	100 kHz
Cosmic Muons	100 Hz
Neutron	10 Hz
IBD	0.01 Hz

Trigger scheme

- Total data rate of ~3 Tb/s
- Triggers and sophisticated online data reduction to handle data rate
- Counting peaks over threshold in local timewindow
- PSD algorithm developed for neutron signals ~80% efficient.



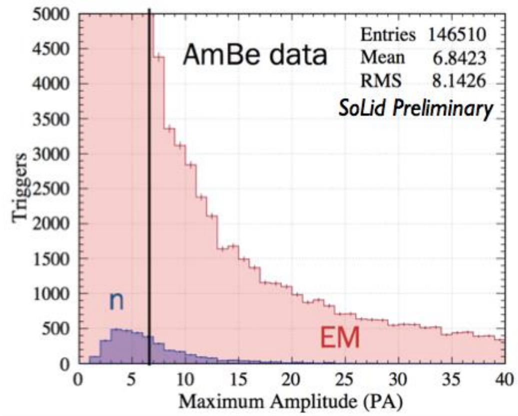


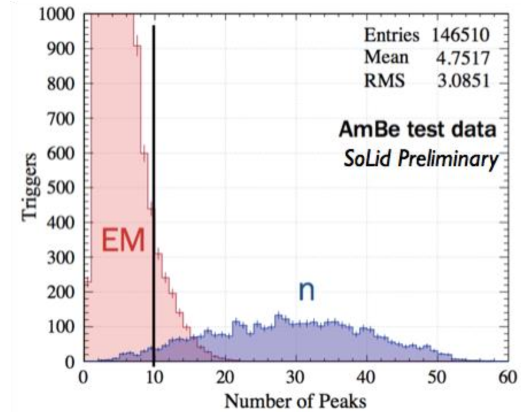
SoLiD

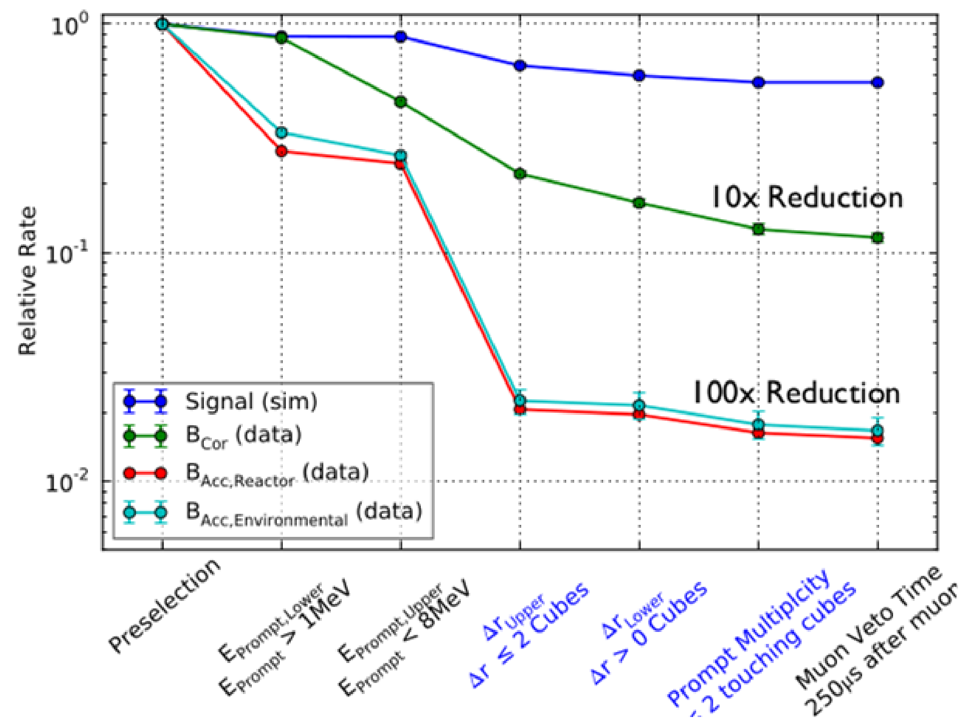
SoLid signal identification

- Large buffer around neutron delayed signal (700µs and 7 planes) to collect prompt signal
- Positron (EM) and neutron signals discriminated based on pulse shape (peaks over threshold)
- IBD signal identified by
  - $\Delta t = t_{delayed} - t_{prompt}$
  - $\Delta r = |r_{delayed} - r_{prompt}|$
  - Prompt energy
  - Others include multiplicity, directionality and fiducial layer
- Simple cut based analysis shows significat reduction in backgrounds

Prototype results







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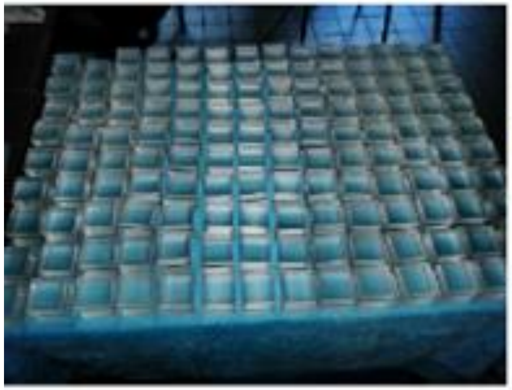
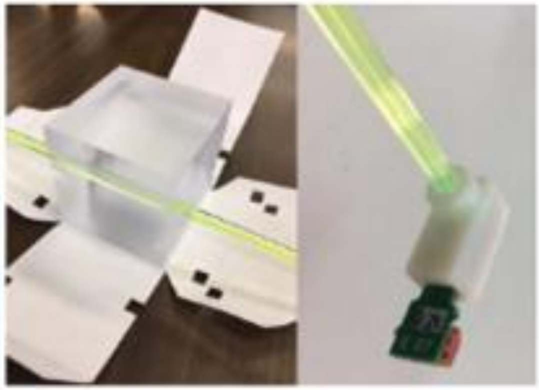
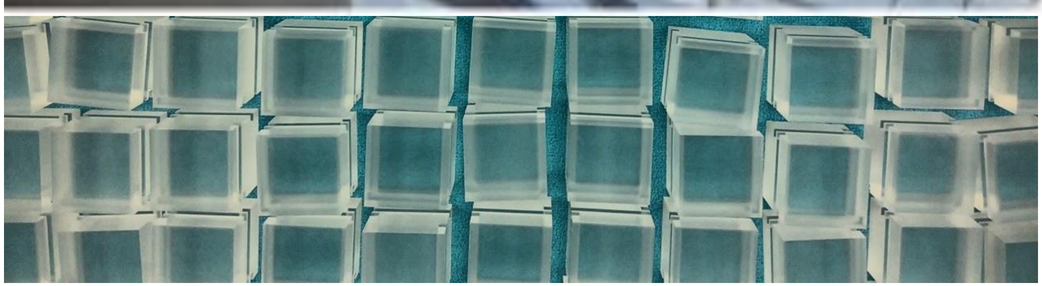
Plane construction and qualification

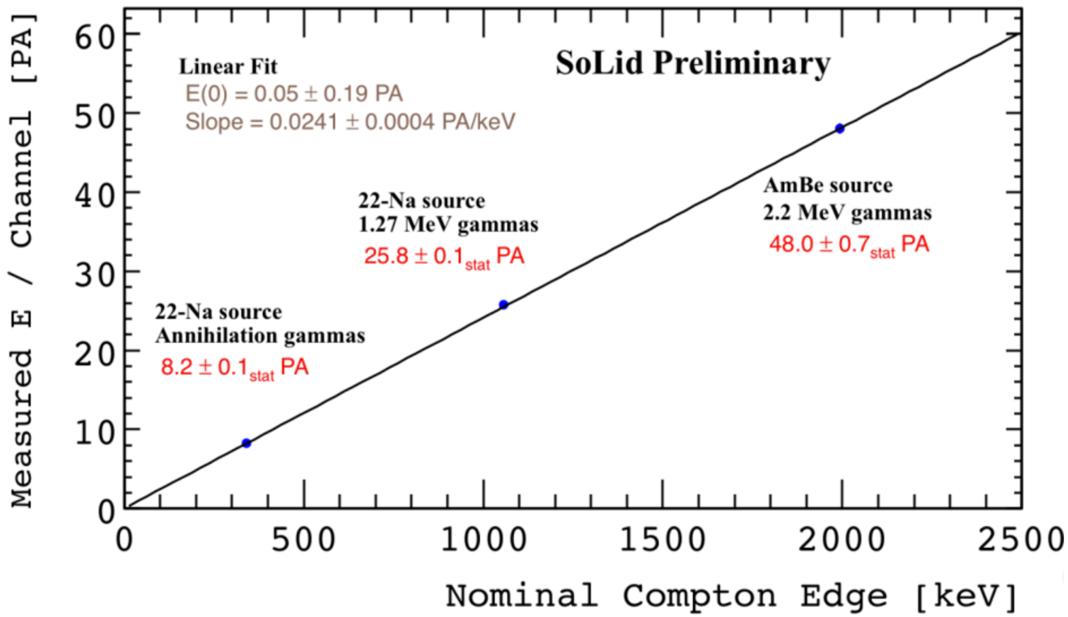



- ~13 000 cubes manually washed, weighted, wrapped, stacked,...
- Planes, electronics and software qualified before installation with automated calibration robot

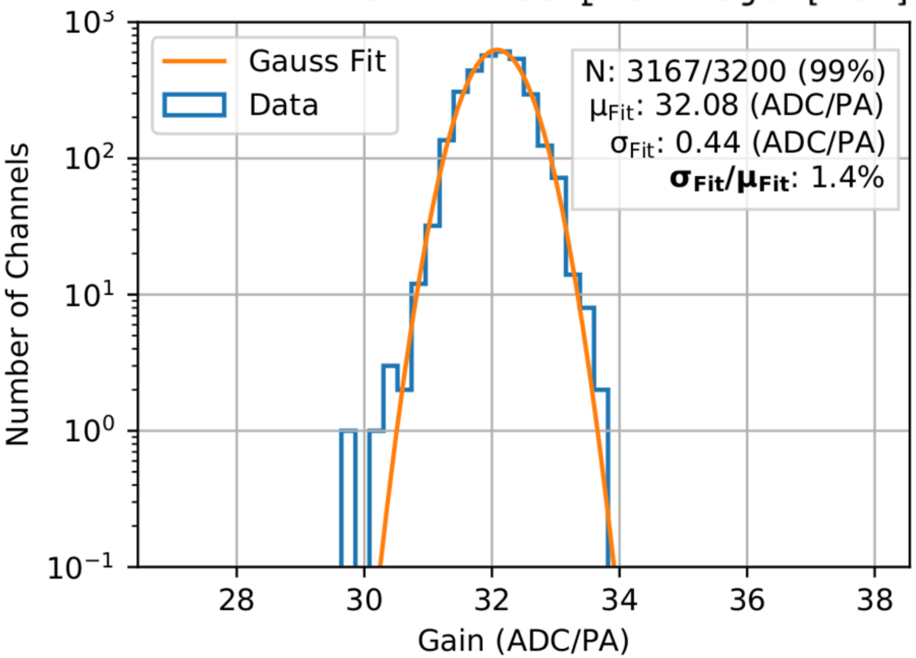




Optical performance

- Different sources show high linearity over wide range
- combined with pure ^{235}U fuel this gives a strong handle on 5MeV distortion



- 99% of 3200 channels operational
- Amplitude response calibrated to high quality, spread ~1,4%



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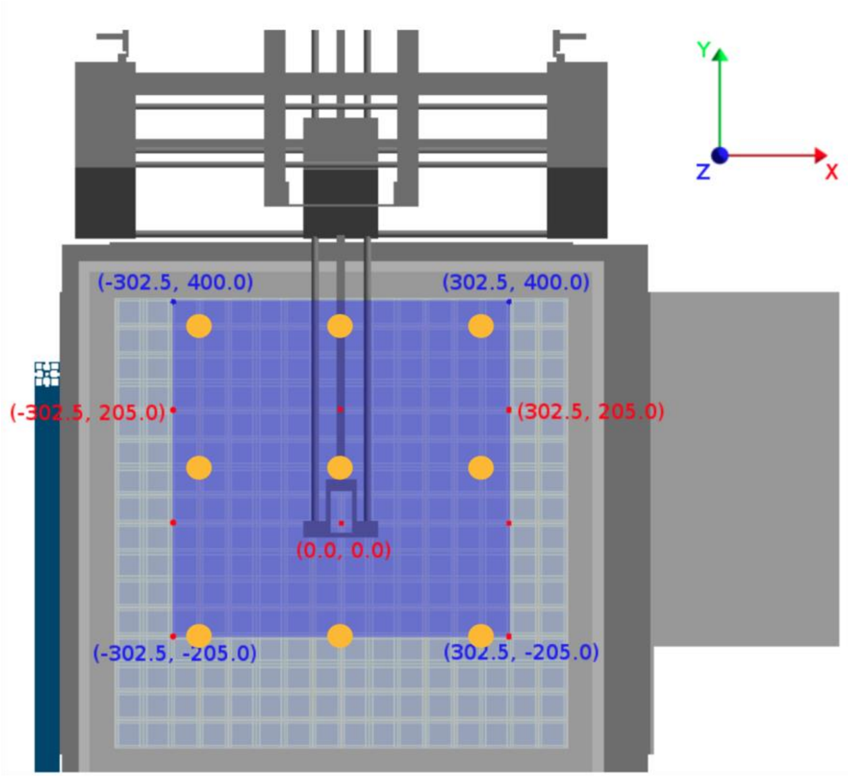
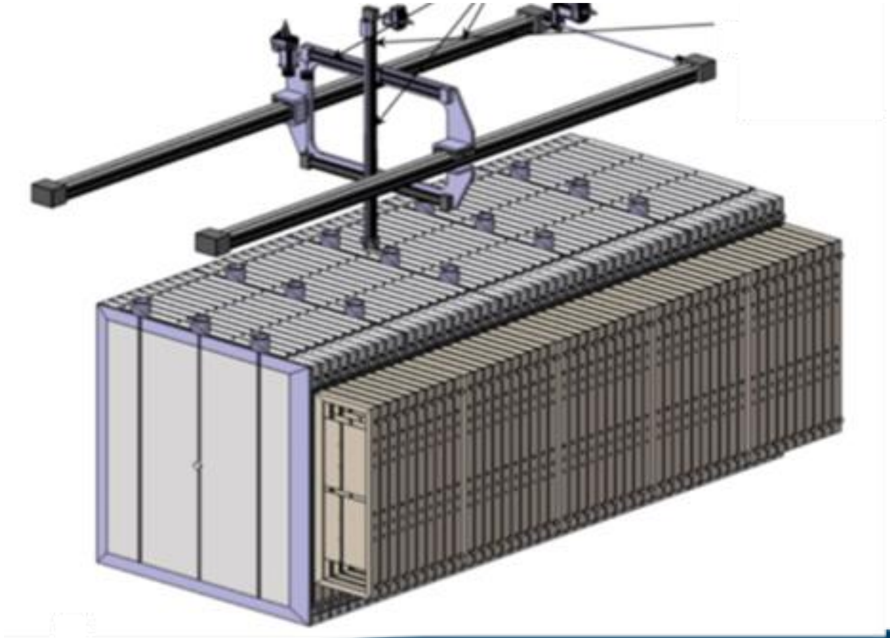
Automated calibration

- Automated calibration robot in situ (CROSS)
- Sits above detector planes
- Mechanically opens gap between sets of ten planes
- Source free to move in gap





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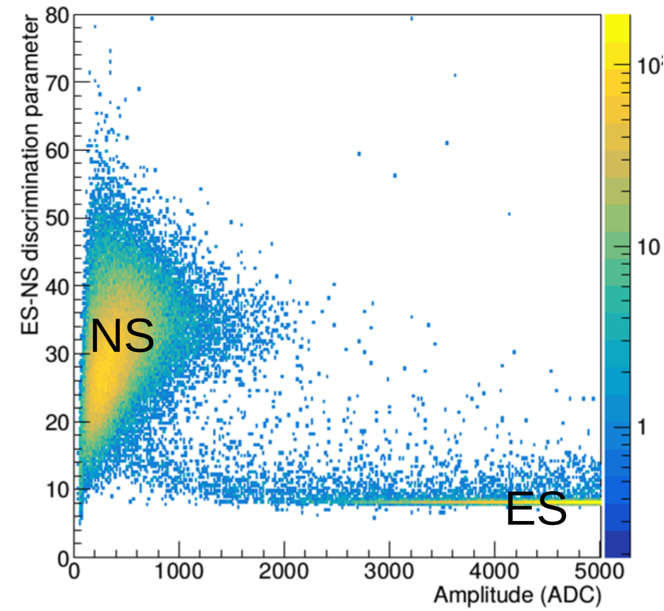
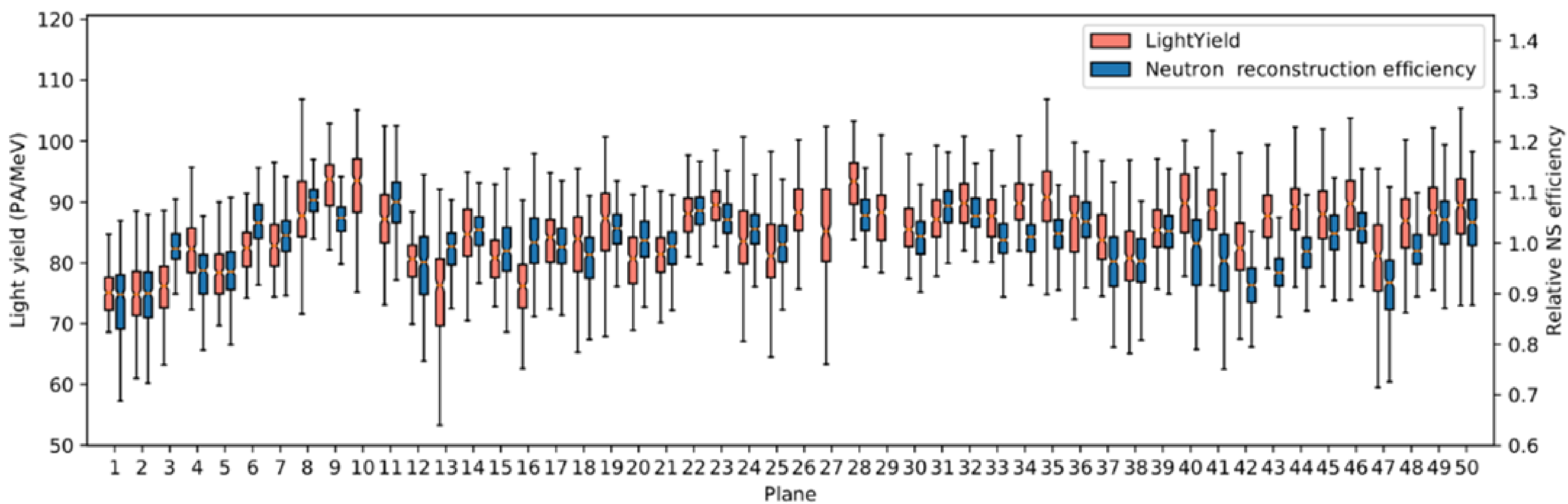
Calibration results at BR2 reactor

- Homogeneous response achieved with highly segmented detector
- Light yield of >70 pA/MeV
- Clear neutron identification after neutron trigger
- Homogenous neutron reconstruction efficiency during commissioning of > 75%
- Linear energy response confirmed with first gamma sources. More sources available





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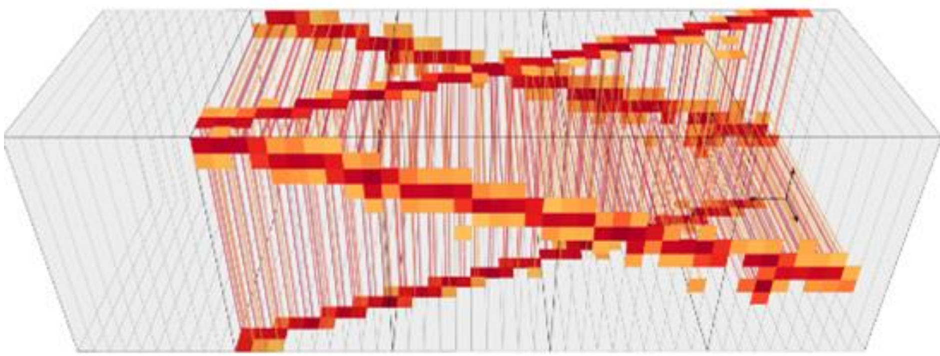
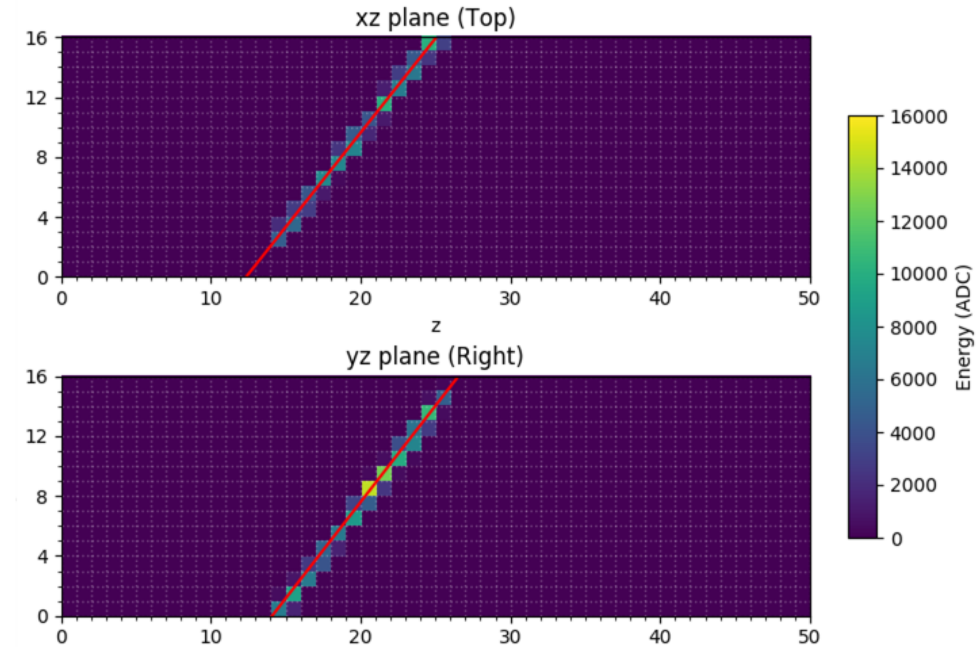
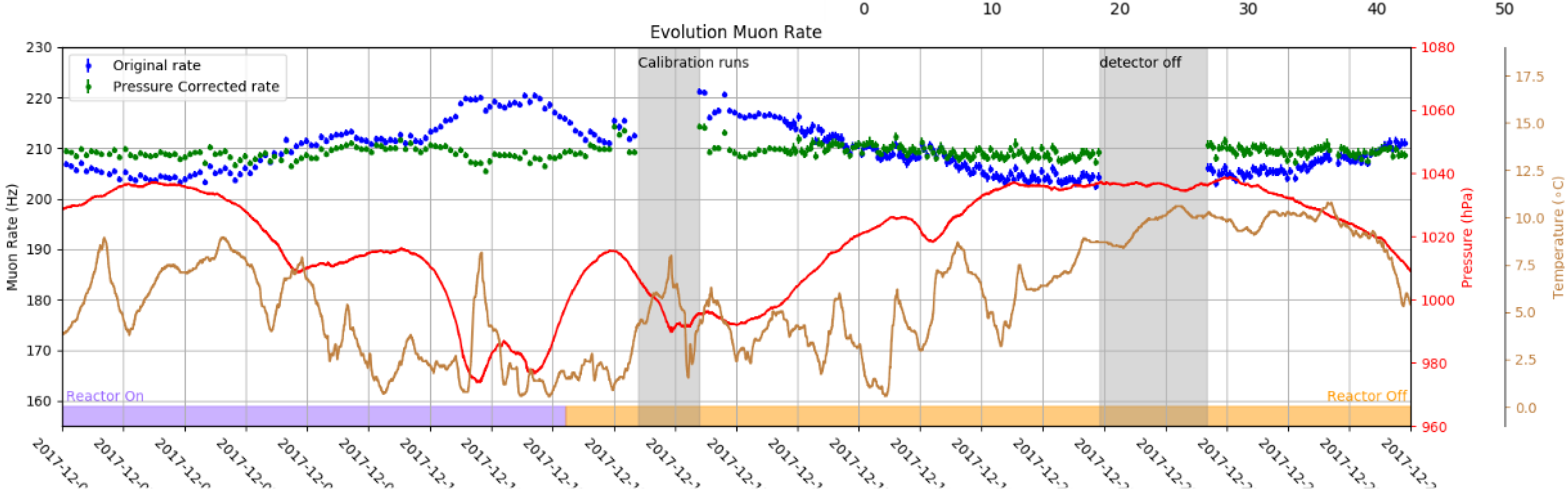
Muon reconstruction

- Constant corrected muon rate
- Muon tracks used for calibration







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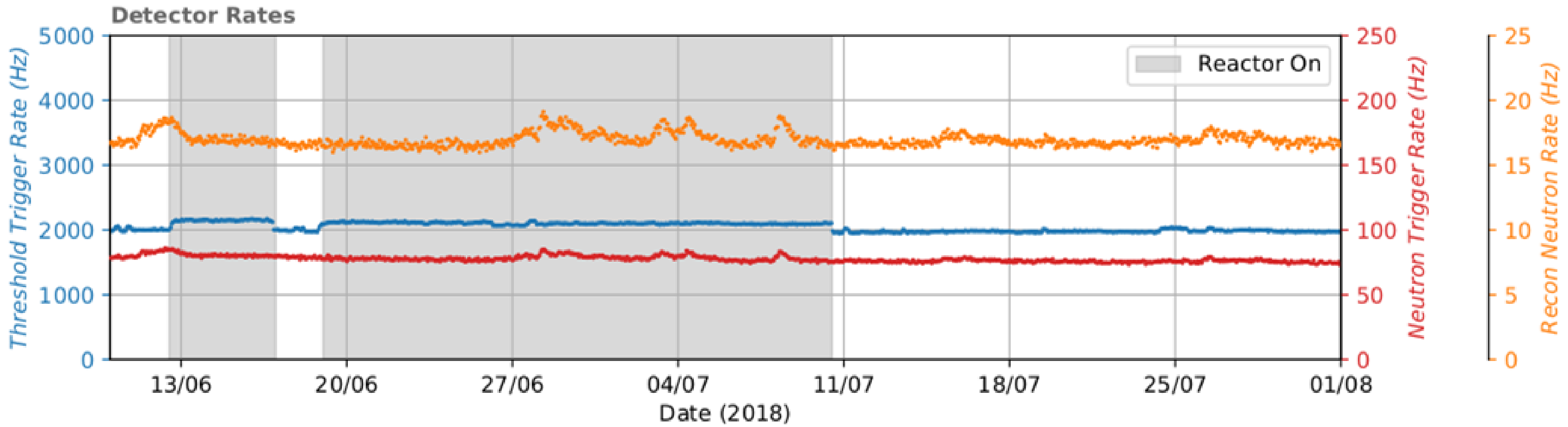
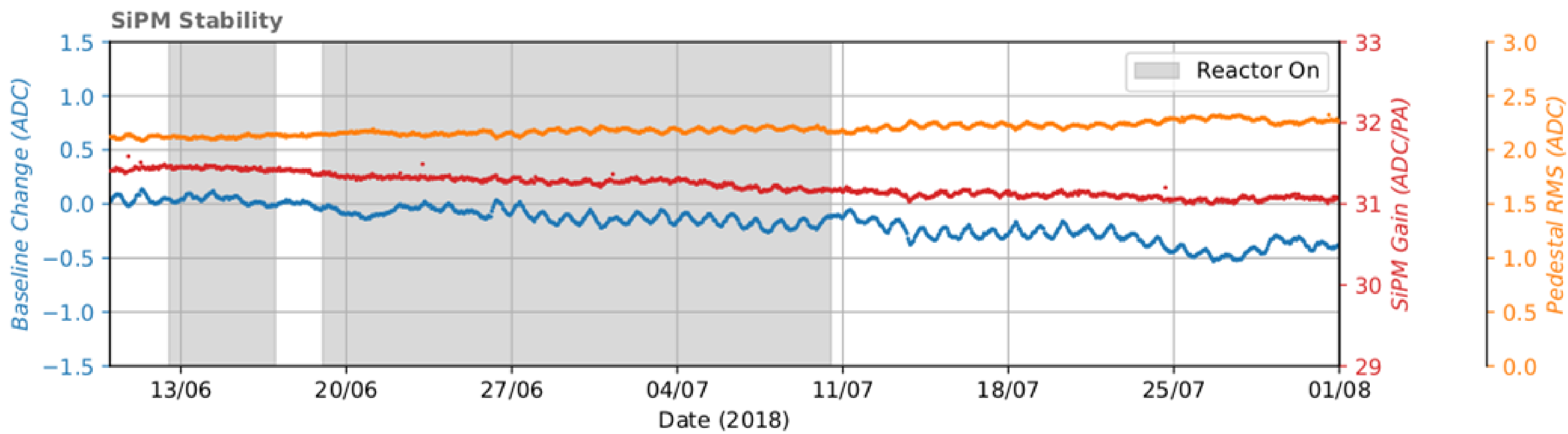
- **Data taking**

Physics data taking

- Highly stable data taking since february, for both reactor on and off
- Physics variables available online for monitoring





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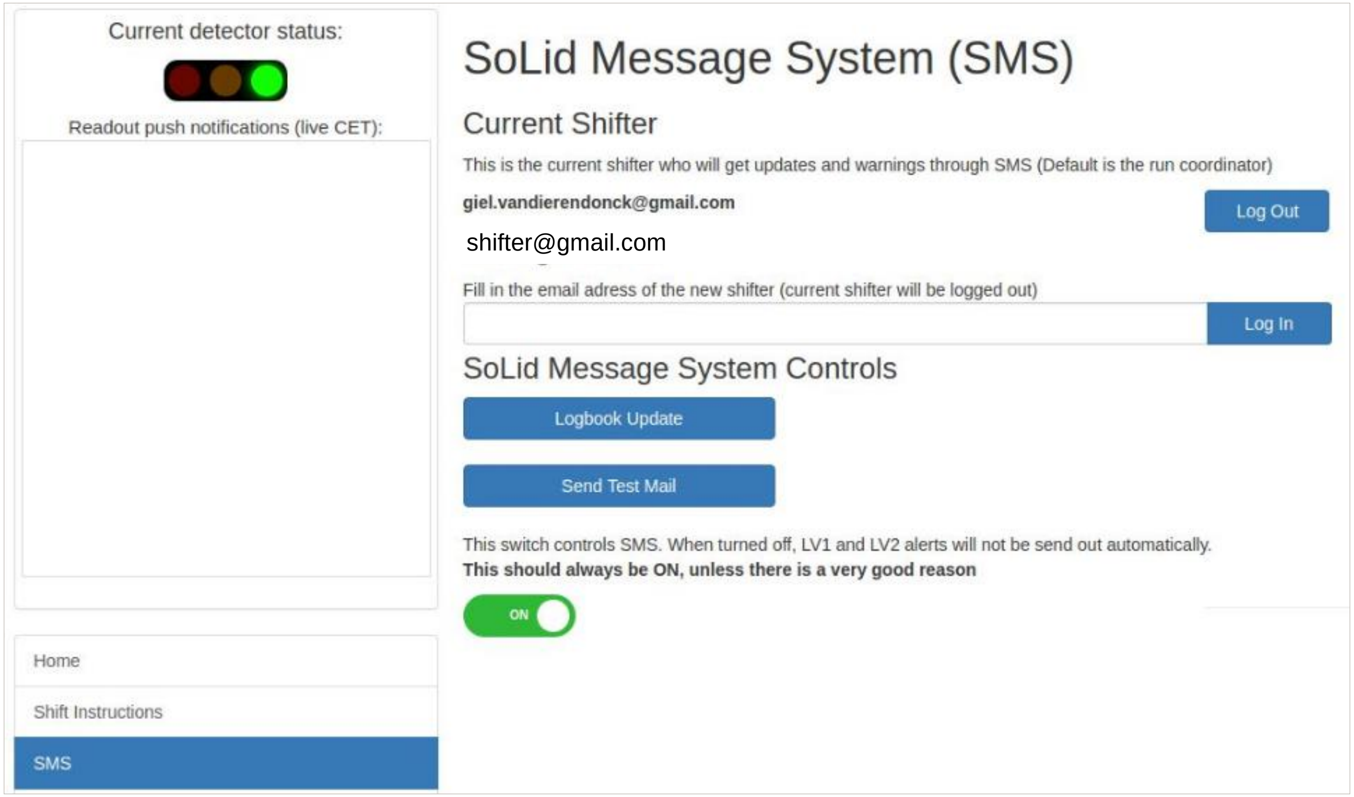
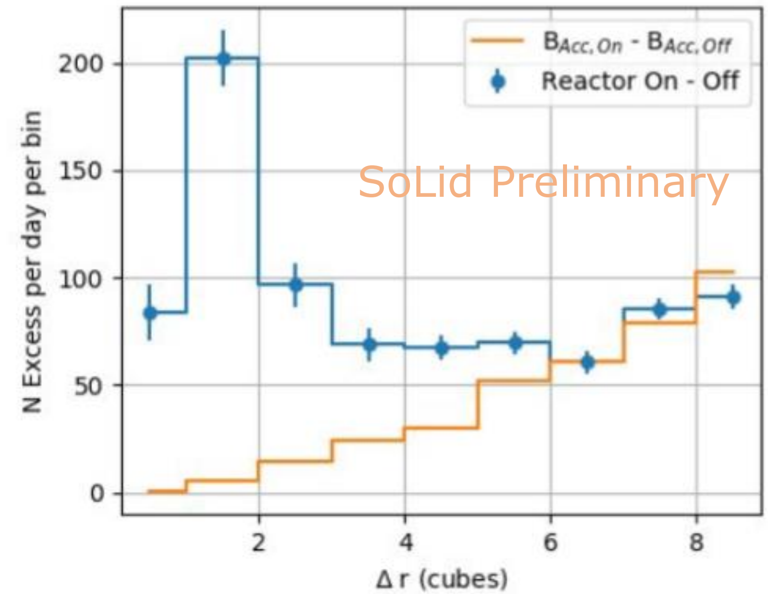
Shift system and remote monitoring

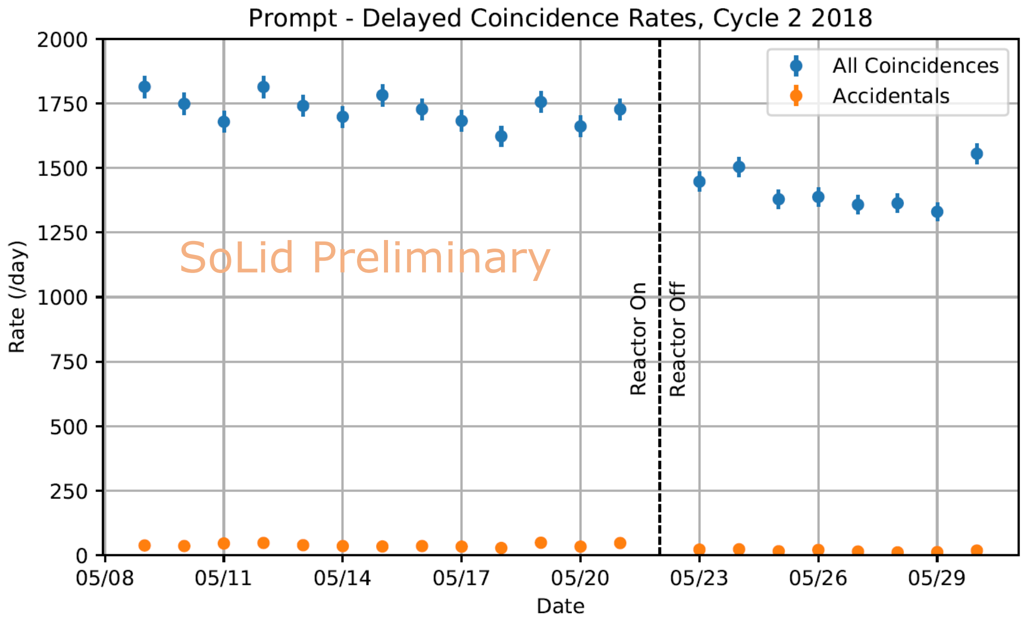
- SoLid Data Quality Management (SDQM) is automated by the the Solid Message System (SMS)
- Automatic updates of monitoring variables are sent regularly
- Alerts are prompted to contact persons when stable data taking is obstructed

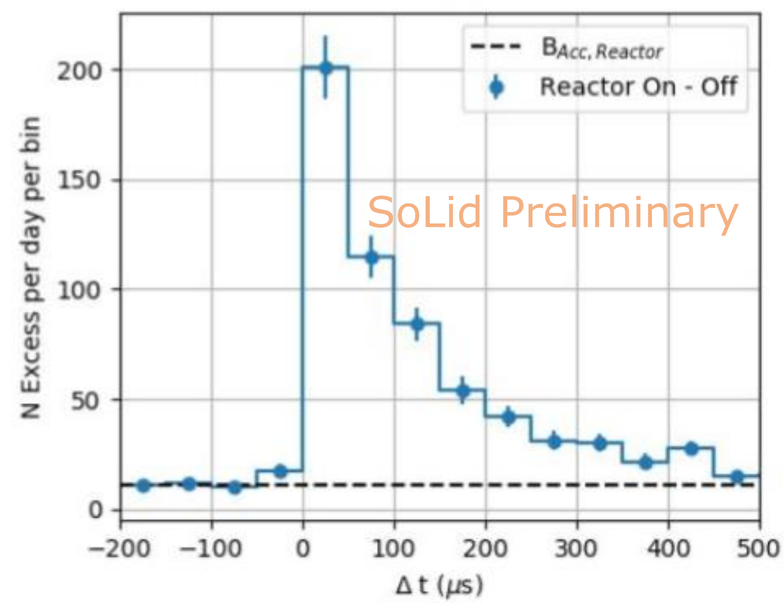


IBD like rates

- Preliminary rate monitoring, based on
  Timing, Topology, Muon veto, Energy selection
- Significantly higher IBD-like rate during reactor ON
- Very low accidental rate
- Behaviour
  - Spatially confined ⍰
  - Time difference consistent
    with thermalised neutron capture ⍰



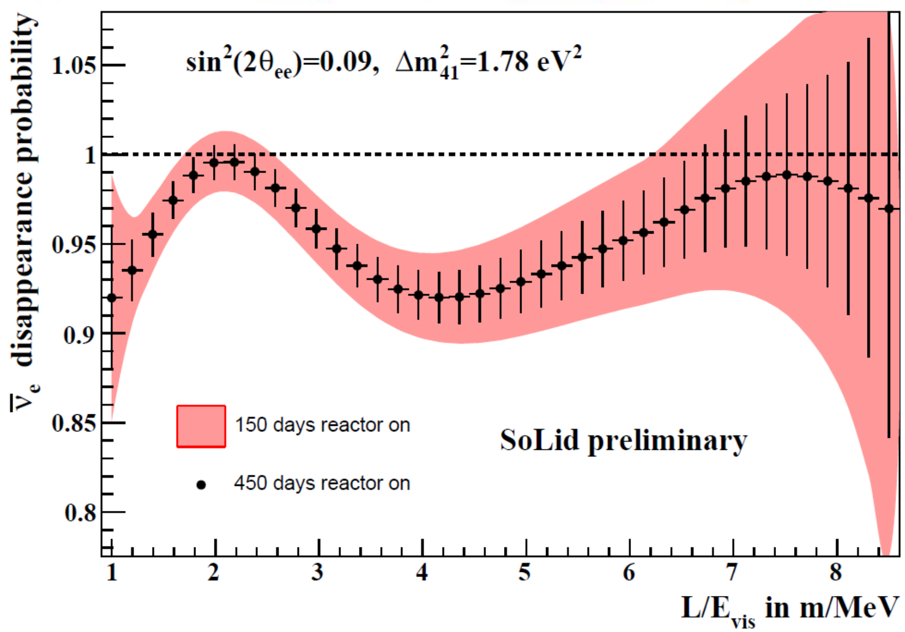


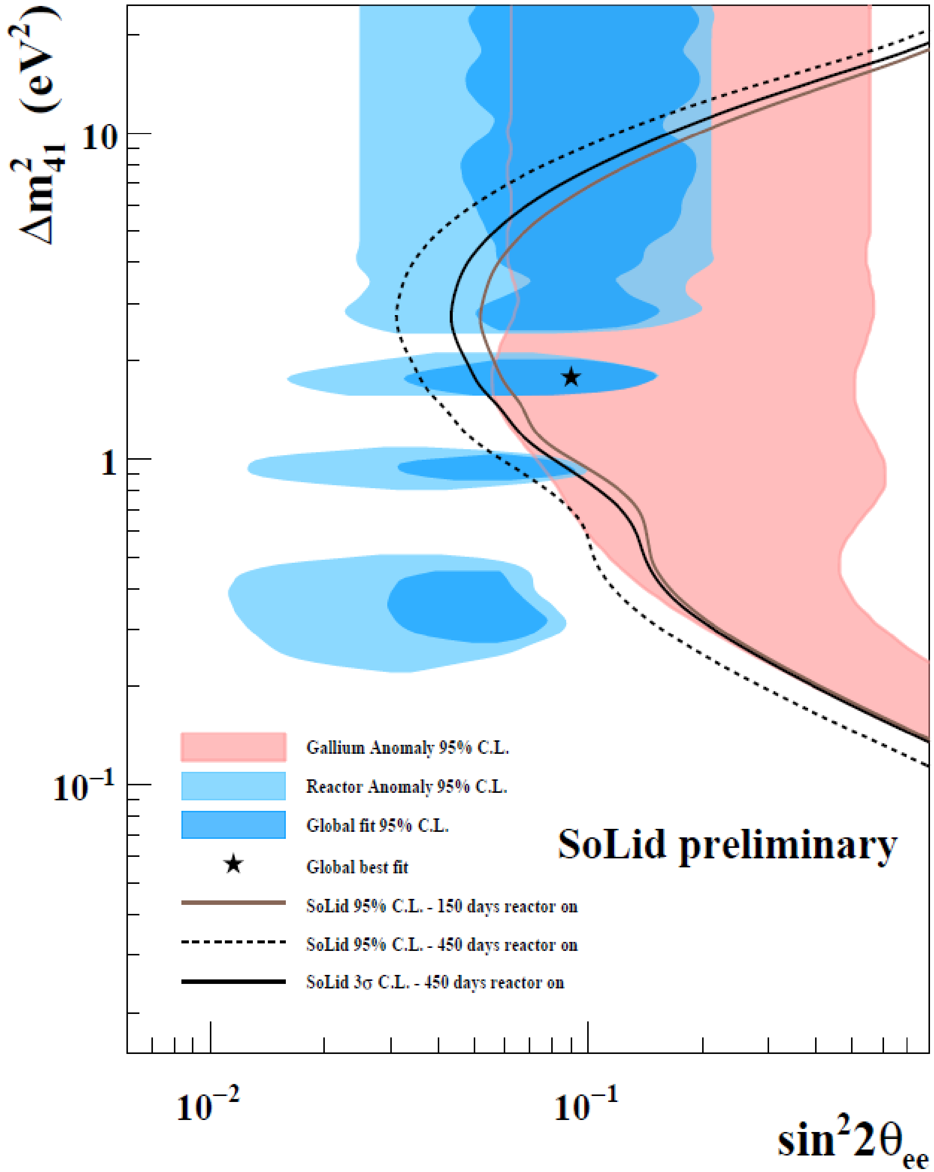


Physics Goal

- Target sensitivity
  - Energy resolution $\frac{\sigma_E}{\sqrt{E\ (MeV)}} = 14\%$
  - IBD efficiency 30%
  - Signal-to-Background 3:1

$P_{ee} \sim 1 - \sin^2(2\theta_{14})\sin\ (1.267\Delta m_{14}^2\ L[m]/E[MeV]\ )$





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Conclusion

- SoLid constructed and deployed sucefully new detector technology
- 1.6 ton detector (Phase1) commissioned end of 2017
- Container design well suited for rapid deployment
- Performance validated with calibration & commissioning data → better than expected
- Operation is smooth, remote shifts simplified to the minimum
- Automatic calibration with source provides precision data for sterile search and spectrum measurement.
- SoLid is taking good quality physics data and observes IBD-like events
- Analyis is being developed
- Detector technology applicable for non proliferation purposes like non intrusive reactor monitoring,

Thank you for your attention

SoLid